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MEMORANDUM REPORT ARBRL-MR-02820

(Supersedes IMR No. 284)

IMPACT THRESHOLDS FOR THE INITIATION OF METAL SPARKING

Warren W. Hillstrom

March 1978

AD No.

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US ARMY ARMAMENT RESEARCH AND DEVELOPMENT COMMAND

BALLISTIC RESEARCH LABORATORY

ABERDEEN PROVING GROUND, MARYLAND

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE	READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER: (14) MEMORANDUM REPORT ARBRL-MR-02820 — 2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle): (6) IMPACT THRESHOLDS FOR THE INITIATION OF METAL SPARKING.	5. TYPE OF REPORT & PERIOD COVERED: (9) Final rept.
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s): (10) Warren W. Hillstrom	8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS: USA Ballistic Research Laboratory (ATTN: DRDAR-BLT) Aberdeen Proving Ground, MD 21005	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS: (16) 1T161102A33E
11. CONTROLLING OFFICE NAME AND ADDRESS: US Army Armament Research & Development Command US Army Ballistic Research Laboratory (ATTN: DRDAR-BL) Aberdeen Proving Ground, MD 21005	12. REPORT DATE: (11) MARCH 1978
	13. NUMBER OF PAGES: 39
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office): (12) 33p.	15. SECURITY CLASS. (of this report): UNCLASSIFIED
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

(18) SBIE

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

(19) AD-E430 002

18. SUPPLEMENTARY NOTES

This report supersedes Interim Memorandum Report No. 284, Aug 1974.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Pyrophoric metals	misch metal
incendiaries	zirconium
metal combustion	titanium
reactive fragments	metal sparking

20. ABSTRACT (Continue on reverse side if necessary and identify by block number) (mba)

Metal cylinders were projected perpendicularly against thick metal plates at varied velocities to determine thresholds of sparking. Pyrophoric metal projectiles such as cerium (misch metal), hafnium, titanium, zirconium and aluminum (Dural) had lower thresholds than the non-pyrophoric metals - iron and copper. Empirical predictions of metal pyrophoricity were confirmed by these results. Impacts on Dural targets had higher thresholds than those on steel targets for given metal projectiles. This is attributed to the lower density of Dural.

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I. INTRODUCTION

Friction and impact sparks have been used by man for untold years to produce heat and light. Flint and pyrites served to start fires for prehistoric man. Later ages used flint-steel and steel-pyrite combinations. Current cigarette lighter sparks are hotter and ignite a wider range of materials than the earlier combinations[1].

The reactive components of most small arms incendiaries are ignited by impact on a target. Since bulk metal components may also contribute incendiary effects by their sparking, a simple, quantitative method was sought to measure impact thresholds of sparking for different metals. Thus, metals that spark easily and/or profusely could be identified by such a test and advantageously incorporated in incendiary munitions. Sparking may be considered a comminution of part of a metal mass with an associated temperature rise and rapid reaction of the particles with the surrounding oxygen or nitrogen in the air. A later report will describe the relative efficiency of different metal sparks for ignition of fuels and other combustible materials.

Pyrophoric metals are defined by Webster as those that spark when scratched or struck. Common pyrophoric metals are cerium, uranium, and zirconium and their alloys. Cerium, for example, is a major component of the common cigarette lighter "flint". In our earlier work[2], two empirical criteria were developed to differentiate between pyrophoric and non-pyrophoric metals. Pyrophoric metals were found to have both (1) a standard free energy of formation per oxygen atom in the metal oxide above 100 and (2) a ratio of metal oxide volume to metal volume above 1.0. From available data on 60 elements, 14 possess properties that suggest pyrophoric behavior. They are aluminum, beryllium, cerium, hafnium, lanthanum, neodymium, plutonium, praseodymium, samarium, thorium, titanium, uranium, yttrium, and zirconium. Pyrophoric and non-pyrophoric metals were compared[2] by heating a sample of non-powdered metal to glowing and striking it with a weight to give it a standard impulse. However, only a few forms of a few metals sparked. For example, zirconium sponge glowed and sparked on impact, but cast zirconium rod did not. The difference in behavior for different forms of the same metal could not be attributed to impurities in the metals. Voids and fractures in the zirconium sponge appear to have increased the metal surface area (external and internal) and thus its reactivity.

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[1] *H. Ellern, "Military and Civilian Pyrotechnics," Chemical Publishing Co., Inc., New York, 1968.*

[2] *W. W. Hillstrom, "Formation of Pyrophoric Fragments," Ballistic Research Laboratories Memorandum Report No. 2306, AD 765447 (1973).*

Many studies of sparking pyrophoricity have been concerned with the ignitability of fine metal powders such as would be formed during sparking[3,4,5,6]. The reactivity and ignitability of small particles, however, is a function of their size and surface reaction history[7,8,9,10].

Brown at the BRL[11] showed that sparks from pyrophoric projectiles were substantial even at air densities corresponding to altitudes as great as 18,300 m. Rae measured the temperature of frictional sparks from titanium and a cerium alloy and found them to be 2700°C.[12]

Recently, Kelley[13] and Blickensderfer[14] measured the sparking radiance of metals abraded on Alundum grinding wheels. They found that soft metals such as brass, copper, aluminum, zinc, magnesium, and beryllium-bronze do not spark. Hard metals such as tool steels and moderately reactive metals such as zirconium, vanadium, columbium, and

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[3] *C. R. Schmitt, J. Fire and Flammability, 2, 157 (1971).*

[4] *I. Hartman, J. Nagy, and H. Brown, "Inflammability and Explosibility of Metal Powders," BMRI 3722 (1943).*

[5] *B. Kopelman and V. B. Compton, Metal Progress, 63, (2), 77 (1953).*

[6] *J. Sehr, Staub, 22, (11), 494 (1962) as translated in Picatinny Arsenal Technical Memorandum 1677, AD 470099 (1965).*

[7] *G. E. Zima, "Pyrophoricity of Uranium in Reactor Environments," AEC HW-62442 (1960).*

[8] *L. Baker, Jr., J. G. Schnizlein, and J. D. Bingle, J. Nucl. Mat., 20, 22 (1966).*

[9] *I. Hartman, J. Nagy, and M. Jacobson, "Explosive Characteristics of Titanium, Zirconium, Thorium, Uranium and Their Hydrides," BMRL 4835 (1951).*

[10] *R. B. Smith, Nucleonics, 14 (12), 28 (1956).*

[11] *N. Brown, "Size and Duration of Sparks Produced by Impact of Steel and Pyrophoric Simulated Fragments on Thin Metal Plates," Ballistic Research Laboratories Report No. 638 (1948).* (AD #800519)

[12] *D. Rae, Combustion and Flame, 5, 341 (1961).*

[13] *J. E. Kelley and R. Blickensderfer, "Spark-Shower Radiance of Metal Grinding Sparks," BMRI 7902 (1974).*

[14] *R. Blickensderfer, J. E. Kelley, D. K. Deardorff, and M. I. Copeland, "Testing of Coal-Cutter Materials for Incendivity and Radiance of Sparks," BMRI 7713 (1972).*

manganese have a high sparking tendency. Dery[15] reported a test in which a rod rapidly arcs across a rusted steel block. Three commercial casting alloys and a number of experimental aluminum alloys were tested for incendiarism in flammable methane-air mixtures. The harder alloys and those containing silicon tended to be more incendiaristic.

A more applicable impact test was needed to quantitatively distinguish between pyrophoric and non-pyrophoric metals for incendiary applications and also to test the validity of the empirical pyrophoricity criteria. This report describes a gun test developed to accomplish these objectives and the experimental results obtained using it.

II. PROJECTILES AND TARGETS

Metal samples were used as obtained from the suppliers. Pure zirconium (Johnson Matthey Chemicals, Ltd., Specpure Grade) was purchased from Fisher Chemical Co., Pittsburgh, Pa. Analysis showed less than 600 ppm impurities, including less than 200 ppm hafnium. Zirconium as Commercial Grade 11 was supplied by Amax Specialty Metals, Inc., Akron, New York. Analysis showed the major contaminants to be iron and chromium at 0.18% total, with zirconium and hafnium at greater than 99.5%. Rods of misch metal alloys were purchased from Ronson Metals Corporation, Newark, N.J. Misch metal grades, 75M2 (75% rare earths, 23% iron, 2% magnesium), 95M (95% rare earths, 5% magnesium), and 100X (97.5% rare earths and 2.5% magnesium) were used. A typical analysis of the rare earths in misch metal is 53% cerium, 24% lanthanum, 16% neodymium, 5% praseodymium, 2% other rare earths. Pure cerium (99.9%) ingots were purchased from Research Organic/Inorganic Chemical Corp., Sun Valley, California, and carefully machined to the desired shapes. Pure titanium (99%), 2024-T3 Dural (Mn, 0.30-0.90; Fe, 0.5; Si, 0.5; Cr, 0.10; Zr, 0.10-0.25; Cu, 3.8-4.9; Cd, 0.05-0.20; Mg, 1.2-1.8; Zn, 0.25; the remainder aluminum) and hard copper rods were obtained locally. Pure hafnium was obtained from Amax Specialty Metals, Inc., Akron, New York.

The target and projectile hardnesses are shown in Table I. The hardnesses of mild steel, pure hafnium, pure titanium, soft and hard copper were measured on a Rockwell Tester and converted to Brinnell Numbers, while the others were obtained from the suppliers.

[15] *D. H. Desy, L. A. Neumeier, and J. S. Risbeck, "Methane Ignition by Frictional Impact Between Aluminum Alloys and Rusted Steel," BMRI 8005 (1975).*

Table 1. Target and Projectile Hardnesses

Metal	Brinnell Hardness No.
Targets	
Soft Copper	62
Dural, 2024-T3	120
Mild Steel	140
Dual Hard Steel Armor (MIL S46099)	500
Projectiles	
Hard Copper	96
Misch Metal, 95M	107
Dural, 2024-T3	120
Pure Zirconium	140
Pure Hafnium	160
Misch Metal, 75M2	160
1095 Steel	170
Grade 11 Zirconium	180
Pure Titanium	210

III. EXPERIMENTAL EQUIPMENT AND PROCEDURE

Right circular cylinders were prepared from each of the projectile materials. They were launched using lexan or wooden sabots except for several copper, steel, and titanium projectiles which were launched full bore.

A diagram of the test arrangement is shown in Figure 1. Firings at velocities less than 300 m/s were made with a 0.50 cal smoothbore barrel on a compressed gas gun using nitrogen. Velocities above 300 m/s were achieved with a 0.30 cal smoothbore propellant gun. Striking velocities were determined by velocity screens positioned at 0.5, 1.0 and 2.0 meters from the target. The timer interval between projectile breakage of the two screens was displayed on a TSI Model 385R interval counter. Velocities were calculated from the time intervals.

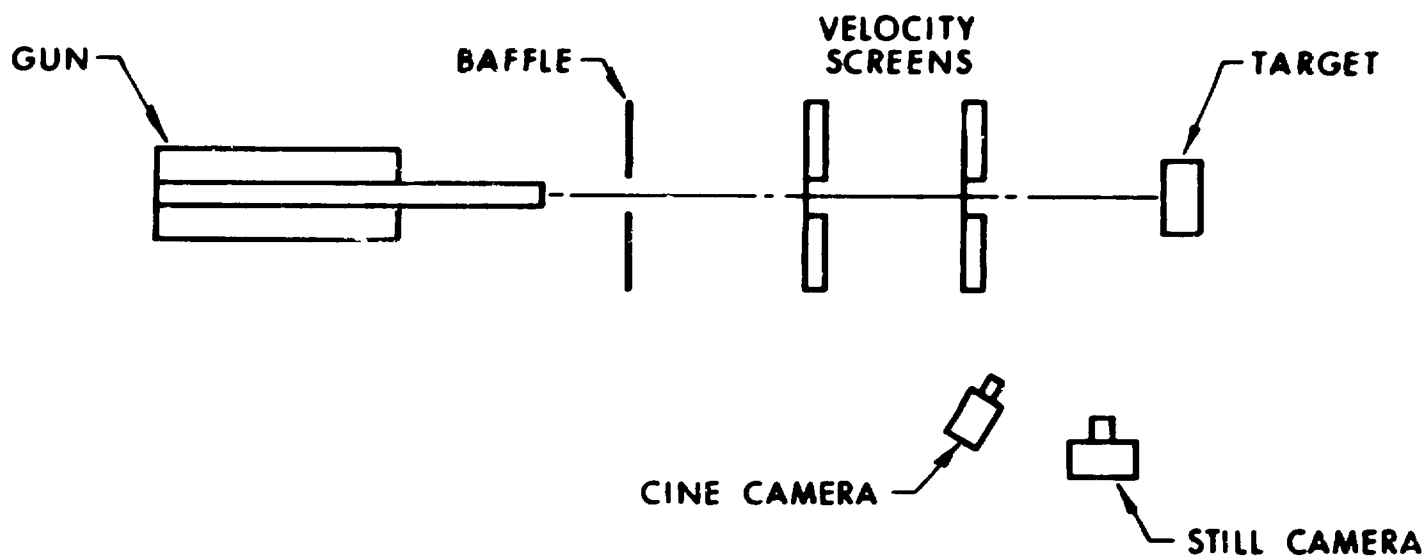

Figure 1. Test Arrangement

The targets were secured to a rigid steel mount and aligned to give normal impacts. Firings were made at distances between the gun muzzle and the target of 1.8 and 6 meters. The Dural targets were 6.35mm thick. The mild steel block was 38.1mm thick and sanded to remove any rust present on the impact surface. The armor plate was 7.9mm thick. The soft copper plate was 3.25mm thick. Additional firings were conducted against 1.6mm thick sheets of 2024-T3 Dural to compare sparking and projectile mass loss after penetration.

Open shutter still photographs in the darkened room were made with Polacolor 58 film in a 4x5 Speed Graphic camera. Impacts were also filmed at 400 frames/sec on 16mm Kodak Ektachrome EF 7241 film. Visual observation through heavy glass ports and still photographs furnished criteria for sparking. "Border" sparks were recorded when at least two spark trails or a flash were observed. A "yes" was recorded when a large array of sparks or a large and persistent flash occurred. The sparking threshold was set as the lowest velocity which consistently gave "border" or "yes".

A series of at least 5 tests over a range of velocities was made to determine each threshold. The tests were designed to give one or more velocities within 50 m/s of the threshold. The pertinent firing test data are recorded in Appendix A.

IV. SPARKING ON IMPACT

Aluminum, cerium, hafnium, titanium, and zirconium are predicted to be pyrophoric metals[2]. Sparking thresholds were determined for these metals and/or their alloys as well as the non-pyrophoric metals--steel and copper. Thresholds were determined on the basis of projectile velocity since a comparison of thresholds for 0.14 and 0.85 gm titanium projectiles striking mild steel showed that variation of projectile mass did not appreciably affect sparking thresholds (183 and 152 m/s, respectively). The corresponding kinetic energies are 2.6 newton-meters and 9.8 newton-meters.

A. Misch Metal and Cerium

Cylinders of the misch metal alloys and cerium alone were launched against both steel and Dural targets. Thresholds of sparking for 75M2 misch metal alloy are summarized in Table II.

Table II. 75M2 Misch Metal Sparking Thresholds

Projectile Mass, Grams	Velocity Ft/Sec	Velocity m/s	Kinetic Energy, N-M	Target
0.24	396	120	1.7	Dural
0.26	367	112	1.6	Mild Steel

Misch metal sparks readily and produces a bright display from impacts at velocities above the threshold. An example of misch metal sparking is shown in Figure 2. The 75M2 cylinder weighed 1.44 gm and traveled at 240 m/s (800 ft/sec) against mild steel. The point of impact is in the center of the photograph and secondary impacts of fragments and sparks against the mild steel mount may be seen at the bottom of the picture. This is contrasted with the impact against Dural as shown in Figure 3 (0.16 gm moving at 272 m/sec).

The sparks from cerium and the cerium alloys (misch metal) are similar in appearance and intensity to those described above from 75M2 misch metal. The thresholds were not measured for each alloy, but sample firings indicate similar, low thresholds. Sparks from impacts above the thresholds are shown in the following photographs. Figure 4 shows an impact of cerium on mild steel at 205 m/s (674 ft/sec). Figure 5 shows the 95M cylinder (0.136 gm) moving at 268 m/s (879 ft/sec) against mild steel. Figure 6 shows the 100X cylinder (1.43 gm) impacting against mild steel at 215 m/s (707 ft/sec).

B. Titanium

Sparking thresholds for titanium projectiles are summarized in Table III.

Table III. Titanium Sparking Thresholds

Projectile Mass, Grams	Velocity Ft/Sec	Velocity m/s	Kinetic Energy, N-M	Target
0.30	902	275	11.3	Dural
0.85	500	152	9.8	Mild Steel
0.39	530	162	5.1	Steel Armor

The intensity of sparks from titanium impacts is not as bright as those from cerium and its alloys. In fact, at and just above the threshold against Dural, the titanium sparks are seen visually but not recorded on the still or motion pictures. At the threshold against mild steel a few sparks were observed, and although none were on the still photo, some are present on the motion pictures. The threshold on steel armor gave sparks that are recorded faintly on both still and motion pictures. Figure 7 shows the threshold impact on steel armor.

As with misch metal, higher sparking thresholds are measured from titanium impacts against the Dural target compared with the steel targets. Harder materials would be expected to impart a greater shock to the projectile upon impact and could cause a loss of material from the projectile. Thus, the lower thresholds from impacts against steel

Figure 2. 75M2 Misch Metal vs Mild Steel

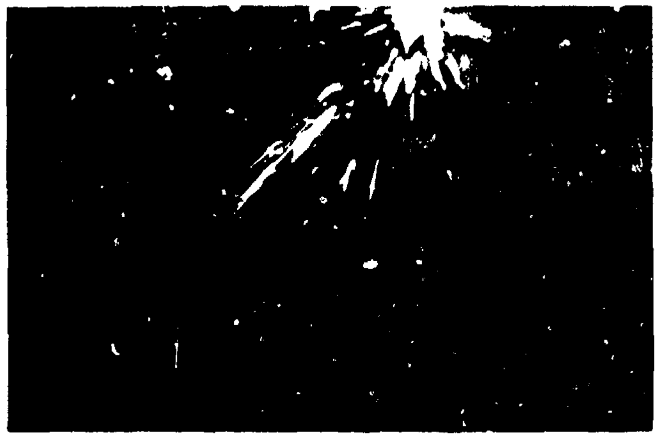

Figure 3. 75M2 Misch Metal vs Dural

Figure 4. Cerium vs Mild Steel

Figure 5. 95M Misch Metal vs Mild Steel

Figure 6. 100X Misch Metal vs Mild Steel

Figure 7. Titanium vs Steel Armor

Figure 8. Zirconium vs Dural

Figure 9. Zirconium vs Mild Steel

Figure 10. Zirconium vs Steel Armor

armor are reasonable. But since the Dural and mild steel targets have similar hardnesses and have consistently different thresholds, target hardness does not appear to explain the differences in the mild steel and Dural thresholds.

After impacts with titanium, indentations were observed in the Dural targets, but not in the mild steel or steel armor targets. The indentations and higher thresholds for Dural targets are probably both the result of the lower density of the Dural. The penetration would lead to a longer time interval of contact during collision and a lower impulsive force acting on the projectile and less loss of particles and sparking.

C. Zirconium and Hafnium

Sparking thresholds for 3mm diameter cylinders of zirconium and hafnium are shown in Table IV.

Table IV. Zirconium and Hafnium Sparking Thresholds

Projectile	Target	Run No.	Projectile Mass Grams	Velocity Ft/Sec	Velocity m/s	Kinetic Energy N-M
Zr	Dural	108	0.93	784	239	27
Zr	Mild Steel	136	0.88	730	222	22
Zr	Steel Armor	48	0.58	822	250	18
HF	Mild Steel	148	0.905	364	111	5.6

Impacts of zirconium on the three targets are shown in photos on the previous page. Figure 8 is an open shutter photograph of the threshold impact of zirconium against Dural. Figure 9 is an open shutter photograph of zirconium against mild steel (0.60 gm at 237 m/s resulting in a kinetic energy of 17 newton-meters). Figure 10 is the threshold impact of zirconium against steel armor. The threshold for sparking of zirconium against the mild steel target was the lowest of the targets. Additional firings of zirconium against steel armor at lower velocities need to be performed to better define this threshold. The thresholds for zirconium against the steel targets are significantly higher than those for titanium or cerium.

The sparking threshold for hafnium is comparable with that of misch metal rather than zirconium and titanium. Hafnium at 13.3 gm/cm^3 is respectively two and three times as dense as zirconium and titanium. Its hardness is similar. The threshold photograph shows no spark, but a spark pattern for 12.2 newton-meters (0.90 gm at 165 m/s) is shown in Figure 11.

D. Dural

2024-T3 Dural was used in place of pure aluminum due to its widespread military usage. Dural has copper and other metals added to increase hardness and corrosion resistance. The sparking threshold for 3mm diameter cylinders of Dural is shown in Table V.

Table V. Dural Sparking Threashold

Projectile	Target	Run No.	Projectile Mass Grams	Velocity Ft/Sec	m/s	Kinetic Energy N-M
Dural	Steel Armor	127	1.04	1156	352	64

The Dural sparking threshold is much higher than those of the other pyrophoric metals. Its sparks are somewhat different in that the spark trials are more erratic. A photograph of an impact is shown in Figure 12. The projectile weighed 0.19 gm and traveled at 908 m/s.

E. Steel and Copper

Sparking thresholds for cylinders of 1095 steel and hard copper are shown in Table VI.

Table VI. Steel and Copper Sparking Threasholds

Projectile	Target	Run No.	Impact Interface Area, Cm^2	Projectile Mass Grams	Velocity Ft/Sec	m/s	Kinetic Energy N-M
Steel	Dural	67	0.312	1.94	1958	597	345
Steel	Steel Armor	40	0.071	0.66	2100	640	135
Copper	Copper	118	0.453	1.89	3266	995	930
Copper	Dural	70	0.453	1.89	3000	914	789
Copper	Steel Armor	144	0.453	2.15	1102	336	121

The steel projectiles launched against steel armor to obtain the threshold were 3mm diameter as were most of the pyrophoric rods already described. The threshold for sparking against steel armor is much higher than those for the pyrophoric projectiles. In order to spark, high velocities were also required for impacts of steel projectiles against Dural. These projectiles and those of copper were launched full bore and had a larger impact interface area than previous projectiles. This large area did not appear to affect the resulting thresholds.

The sparks from steel projectiles were not as intense as those from the pyrophoric cylinders. For example, the open shutter photograph in Figure 13 is from an impact of a steel projectile of 1.94 gm moving at 998 m/s (3274 ft/sec) striking a Dural target. Even at these relatively high velocities and relatively large masses, the sparks are a

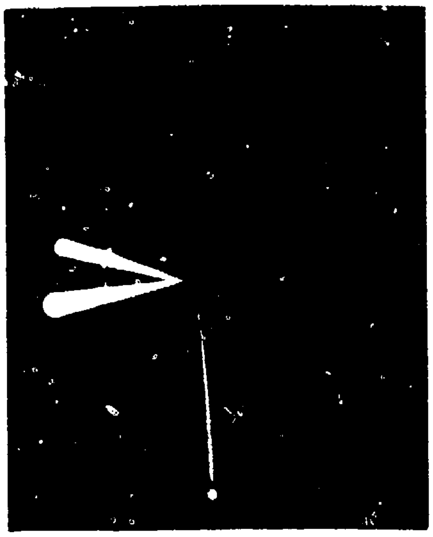

Figure 11. Hafnium vs Mild Steel

Figure 12. Dural vs Steel Armor

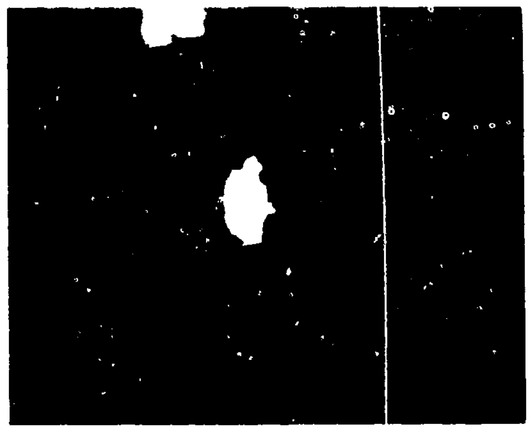

Figure 13. Steel vs Dural

Figure 14. Copper vs Copper

Figure 15. Copper vs Dural

yellow-red color.

For copper impacts on the soft copper target very high velocities or large masses were required to induce sparking. For example, in Figure 14 the 1.88 gm projectile was moving at 1171 m/s (3843 ft/sec) for a kinetic energy of 1289 newton-meters against copper. In Figure 15 the photograph is the threshold impact of the copper projectile of 1.89 gm moving at 914 m/s (3000 ft/sec) for a kinetic energy of 789 newton-meters against Dural. Like steel, copper needs large masses at high velocities for sparking and the resulting sparks are not as intense as pyrophoric sparks.

F. Mass Loss from Impact and Sparking

Mass losses were determined for the impacts of non-pyrophoric and pyrophoric projectiles on targets with and without perforation. In Table VII mass losses are compared with sparking for a range of velocities of copper projectiles striking steel armor without perforation.

Table VII. Copper Mass Loss on Impact

Run No.	Velocity m/s	Initial Mass Gm	Final Mass Gm	Loss Gm	Sparks
143	865	2.16	1.27	-0.89	Yes
144	336	2.15	2.14	-0.01	Some
147	267	2.14	2.13	-0.01	No
145	238	2.15	2.15	0.00	No
146	159	2.15	2.16	+0.01	No

These data show that very small projectile mass losses (ca. 0.5%) are responsible for sparking at/or near the threshold. It can also be seen that quite substantial amounts of material are lost from the projectile at higher velocities. In this test series, the target plate was unchanged after the impacts. Thus, all of the sparks are generated from the material of the projectiles. The projectiles were recovered after impact and are shown in Figure 16.

The mass loss during perforation and sparking was measured for 7.6mm diameter titanium cylinders (except for Run No. 330 which was Grade 11 zirconium) launched against 1.6mm thick 2024-T3 Dural. The projectiles were retrieved from a soft recovering system and are shown in Figure 17. The results are shown in Table VIII.

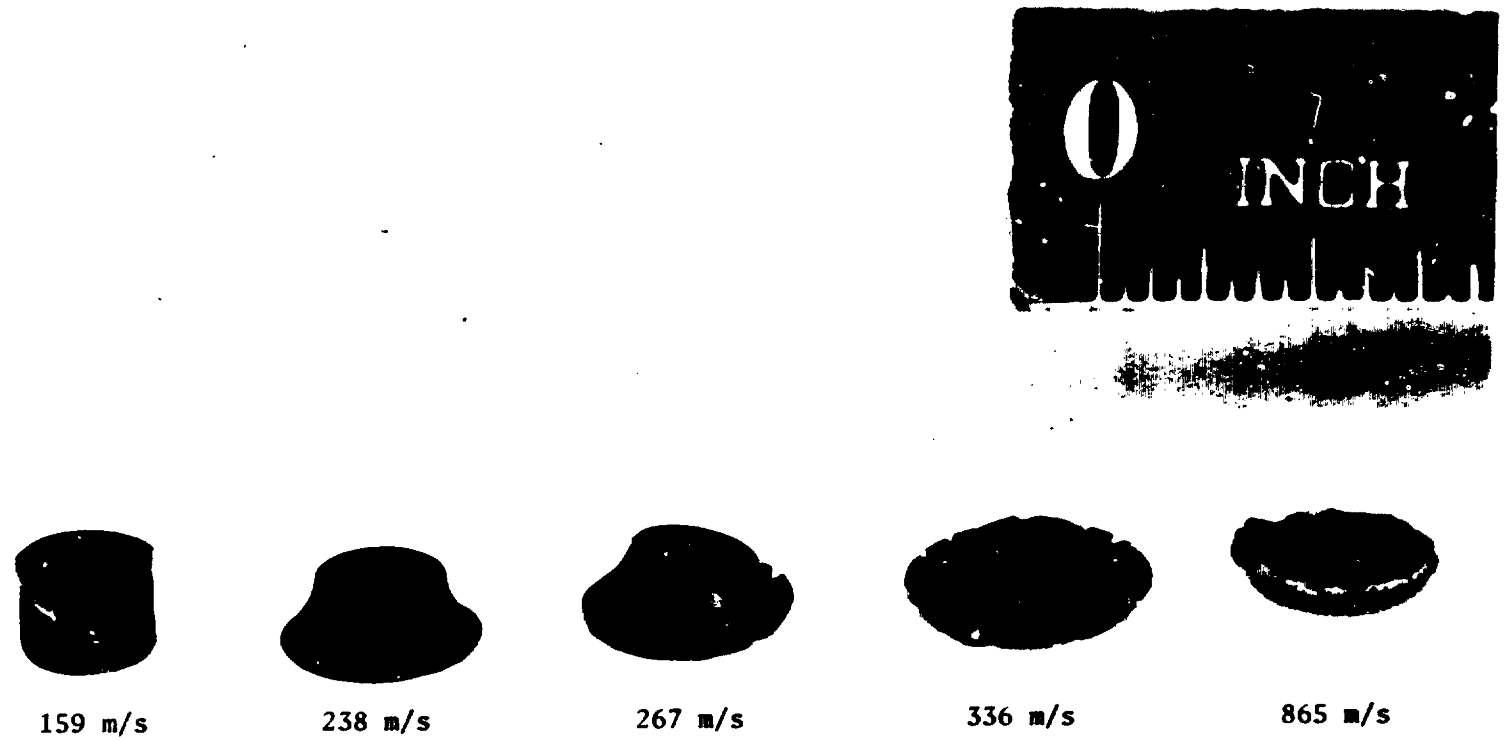

Figure 16. Copper Fragments after Impact on Steel Armor

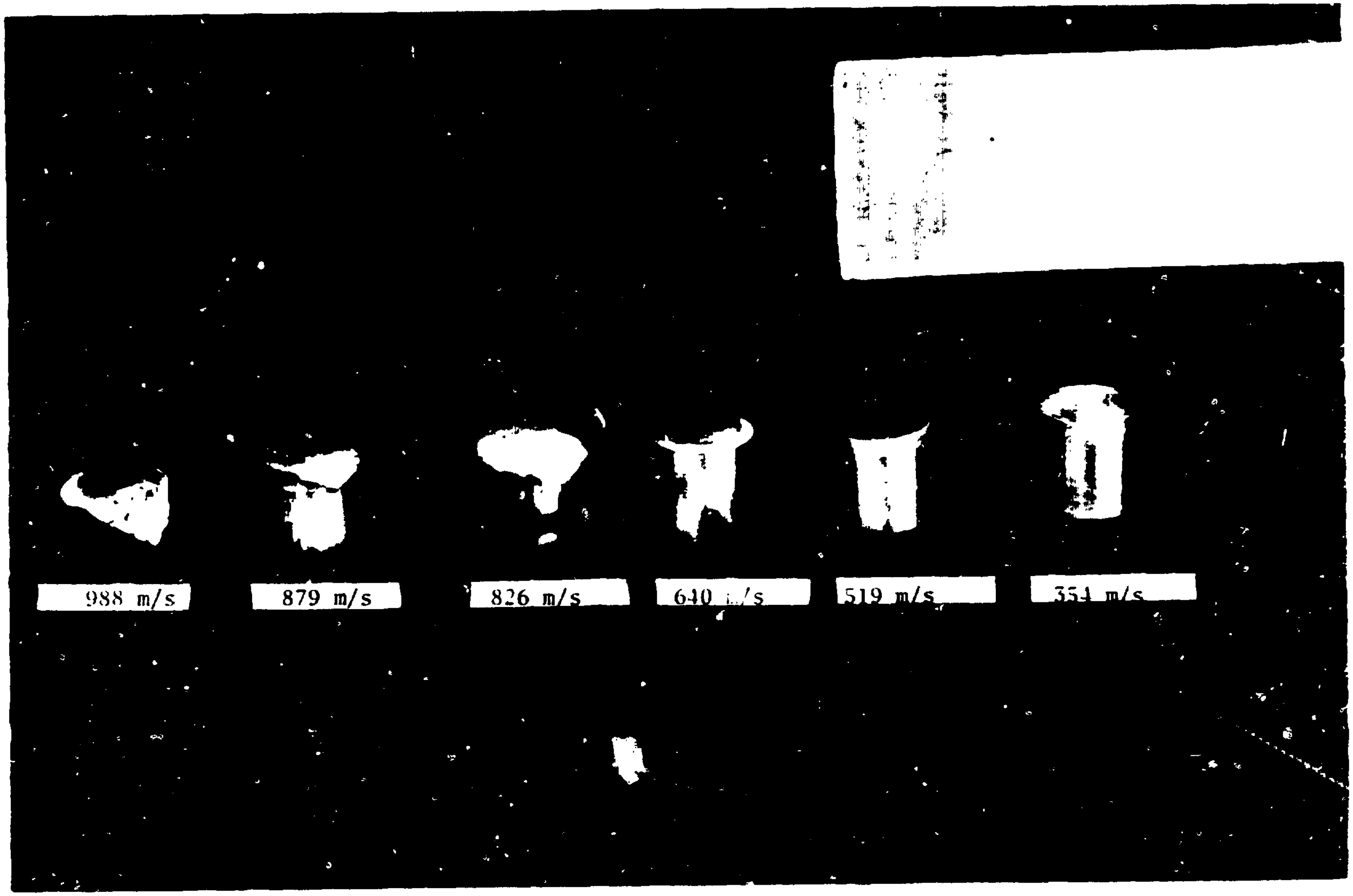

Figure 17. Titanium Fragments after Perforation of Dural Sheet

Table VIII. Titanium Mass Loss on Impact

Run No.	Velocity m/s	Initial Mass Gm	Final Mass GM	Kinetic Energy N-M	Loss GM	%	Sparks	Spark Duration ms
150	988	1.6936	1.5845	825	-0.1091	-6.4	Yes	473
155	879	1.7173	1.6958	664	-0.0215	-1.3	Yes	1
154	826	1.7283	1.7042	587	-0.0241	-1.4	Yes	0.75
152	640	1.7155	1.7157	352	+0.0002	0.0	Some	0.25
151	519	1.7300	1.7302	233	+0.0002	0.0	Some	0.25
153	354	1.7264	1.7268	108	+0.0004	0.0	No	0

All of the projectiles perforated the Dural target. At velocities below 826 m/s some aluminum was apparently transferred from the target to the projectile during penetration resulting in a slight weight increase. Although the projectile mass loss during sparking was small, the spark duration was easily measured by motion pictures at 400 frames/sec. It can be seen that large mass losses and extended spark visibility occur at a velocity nearly twice that required for initial sparking.

All of these impacts are well above the sparking threshold against Dural reported in Section B of this report. However, the thin target sheet used in this test series apparently offered so little resistance to the projectile that higher striking velocities were needed to cause sparking compared with the bulk target materials used in determining the thresholds. This target is applicable to fuel ignition studies which are underway.

G. Metal Sparking Comparisons

Sparking velocity thresholds for the different projectile-target combinations are compared in Table IX.

Misch metal and hafnium projectiles striking mild steel targets had the lowest impact sparking thresholds of the combinations tested. Titanium and zirconium striking mild steel had higher thresholds and Dural striking steel armor targets had the highest threshold of the pyrophoric metal projectiles tested.

The thresholds for projectiles striking Dural targets were generally higher than thresholds for the same metals striking steel targets as shown by misch metal, titanium, and zirconium projectiles. The thresholds for projectile impacts on mild steel and steel armor targets shown in Table IX may be considered to be within experimental error.

Table IX. Velocity Comparison of Sparking Thresholds

Projectile	Impact Interface Area, Cm^2	Thresholds Against Dural m/s	Thresholds Against Mild Steel m/s	Thresholds Aganist Steel Armor m/s
Hafnium	0.071	-	111	-
75M2 Misch Metal	0.071	120	112	-
Titanium	0.071	275	152	162
Zirconium	0.071	239	222	250
Dural	0.071	-	-	352
1095 Steel	0.071	-	-	640
1095 Steel	0.312	59[illegible]	-	-
Copper	0.453	914	-	336

Steel and copper, which were predicted to be non-pyrophoric in Reference 2, have higher sparking thresholds than pyrophoric metals except for copper striking a steel armor target. All of the metal projectiles tested, both pyrophoric and non-pyrophoric metals, flashed or sparked given a sufficiently high striking velocity. During high velocity impacts, small particles are torn from the projectile or target and may be heated by the energy of the impact to a sufficiently high temperature to ionize or to react incandescently with the surrounding air. The pyrophoric metals described in Reference 2 react exothermally with air to raise the metal and metal oxide temperature even further. The resulting incandescent particles or vapors are seen as sparks. The non-pyrophoric metals are not as reactive and higher impact forces are required to produce incandescent impact debris.

The kinetic energies of the projectiles at the impact sparking thresholds are compared in Appendix B. The projectile materials fall into approximately the same order as the thresholds compared by velocity as shown in Table IX. The only change results from misch metal having the lowest kinetic energy with sparking (1.6 newton-meters for misch metal striking a mild steel target compared with 5.6 newton-meters for hafnium striking the same target). Impacts against steel armor targets had the lowest kinetic energies of the three targets for a given projectile material - such as titanium or zirconium. The non-pyrophoric metals - steel and copper - had much higher kinetic energies at the sparking thresholds than the pyrophoric metals.

V. CONCLUSIONS

Projectile impact velocity thresholds for metal sparking furnish an experimental test method to quantitatively distinguish between sparking pyrophoric and non-pyrophoric metals and alloys. The pyrophoric metals in these tests sparked at velocities between 120 and 275 meters/second against Dural targets. The non-pyrophoric metals had much higher thresholds than the pyrophoric metals.

The different projectile materials induced sparking in the following order, misch metal (cerium) > hafnium > zirconium > Dural (aluminum) > steel > copper.

Higher thresholds resulted from impacts against Dural than against the steel targets. This is attributed to the lower density and deeper penetration of the Dural which resulted in lower impulsive force applied to the projectile during impact, leading to less projectile breakup and sparking.

Earlier empirical predictions of metal pyrophoricity using a combination of (1) the free energy of formation of the metal oxide per oxygen atom and (2) the ratio of metal oxide to metal specific volumes are confirmed by the experimental results of these tests since the predicted pyrophoric metals sparked much more readily than the non-pyrophoric metals.

ACKNOWLEDGMENT

The author is grateful to C. Roop and E. Donnelly for their assistance in projecting the cylinders against the targets and S. Golaski for furnishing samples of titanium and for determining metal hardnesses.

APPENDIX A

Firing Test Results

Run	Projectile		Velocity			
No.	Mat'l	Mass, Gm	ft/sec	m/s	Target Mat'l	Sparks
1	Ce	-	674	205	Mild Steel	Yes
2	75M2	1.44	-		Mild Steel	Yes
3	75M2	1.44	695	212	Mild Steel	Yes
4	75M2	1.44	712	217	Mild Steel	-
5	75M2	1.44	709	216	Mild Steel	Yes
6	75M2	1.44	-		Mild Steel	Yes
7	75M2	1.44	692	211	Mild Steel	-
8	75M2	1.44	715	218	Mild Steel	-
9	75M2	1.44	739	225	Mild Steel	Yes
10	Zr	.57	804	245	Mild Steel	No
11	Zr	.57	846	258	Mild Steel	Some
12	Al	-	837	255	Mild Steel	No
13	Zr sponge	.99	730	223	Mild Steel	Some
14	Ti	.51	-		Mild Steel	Some
15	95M	1.42	718	219	Mild Steel	Yes
16	100X	1.435	707	215	Mild Steel	Yes
17	Hot Pure Zr	.57	-		Mild Steel	Some
18	75M2	-	-		Mild Steel	No
19	75M2	.210	-		Mild Steel	Yes
20	75M2	.210	795	242	Mild Steel	Yes

Run No.	Projectile Mat'l	Mass,Gm	Velocity ft/sec	m/s	Target Mat'l	Sparks
21	75M2	.210	870	265	Mild Steel	Yes
22	75M2	.14	982	299	Mild Steel	Yes
23	75M2	.14	-		Mild Steel	Yes
24	75M2	.20	-		Mild Steel	Yes
25	75M2	.145	885	270	Mild Steel	Yes
26	75M2	.15	865	264	Mild Steel	-
27	75M2	.16	893	272	Dural	Some
28	75M2	.15	-		Mild Steel	-
29	75M2	.310	707	215	Mild Steel	Yes
30	75M2	.17	752	229	Mild Steel	Yes
31	95M	.136	879	268	Mild Steel	Some
32	75M2	1.44	671	205	Mild Steel	Yes
33	75M2	1.44	-		Mild Steel	Yes
34	Zr	.56	1943	592	Steel Armor	Some*
35	Zr	.56	2694	821	Steel Armor	- **
36	Zr	.56	2915	888	Steel Armor	-
37	Steel	.66	3215	980	Steel Armor	- **
38	Zr	.56	2179	664	Steel Armor	Yes
39	Steel	-	2375	724	Steel Armor	No
40	Steel	.66	2100	640	Steel Armor	Some
41	Steel	.66	2761	842	Steel Armor	Yes
42	Ti slag	.37	2681	817	Steel Armor	Yes

* some glowing particles

** missed target

Run No.	Projectile Mat'l	Projectile Mass,Gm	Velocity ft/sec	Velocity m/s	Target Mat'l	Spark
43	Ti slag	.37	3019	920	Steel Armor	Yes
44	Ti slag	.37	2604	794	Steel Armor	Yes
45	Zr	.56	1888	575	Steel Armor	Yes
46	Zr	.58	1249	381	Steel Armor	Yes
47	Zr	.57	1047	319	Steel Armor	Yes
48	Zr	.58	822	251	Steel Armor	Some
49	Steel	.69	1196	365	Steel Armor	No
50	Ti	.39	1385	422	Steel Armor	Yes
51	Ti	.39	530	162	Steel Armor	Some
52	Ti	.39	1307	398	Steel Armor	Yes
53	Steel	1.94	2431	741	Dural 1.6 mm	No
54	75M2	1.45	2375	724	Dural 1.6 mm	Yes
55	75M2	1.39	2496	761	Dural 3.2 mm	Yes
56	75M2	1.41	2224	678	Dural 2X 6.4 mm	Yes
57	Zr	.648	2657	810	Dural 1.6 mm	Some
58	Zr	.596	2443	745	Dural 3.2 mm	Some
59	Zr	.622	2589	789	Dural 3.2 mm	Some
60	Zr	.609	2637	804	Dural 6.4 mm	Some
61	Zr	.907	2535	773	Dural 6.4 mm	Some
62	Zr	.298	1942	592	Dural 1.6 mm	Some
63	Zr	.304	629	192	Dural 2.0 mm	No *
64	Zr	.298	2295	670	Steel Support	Yes**

* unburned powder

** missed target but hit support

Run No.	Projectile Mat'l	Projectile Mass, Gm	Velocity ft/sec	Velocity m/s	Target Mat'l		Sparks
65	Zr	.324	2259	689	Dural	2.0 mm	Some*
66	Cu	1.91	1591	485	Dural	2.0 mm	No
67	Steel	1.94	1958	597	Dural	6.4 mm	Some**
68	Steel	1.94	3274	998	Dural	6.4 mm	Some**
69	MM	1.45	2353	717	Dural	6.4 mm	Yes
70	Cu	1.89	3000	914	Dural	2.0 mm	Some
71	Zr	.596	1173	358	Mild Steel		Yes
72	Zr	.602	776	237	Mild Steel		Some
73	Zr	.603	2677	816	Mild Steel		Yes
74	Ti	.141	999	304	Mild Steel		Some
75	Ti	.142	860	262	Mild Steel		Some
76	Ti	.147	999	304	Mild Steel		Some
77	Ti	.156	849	259	Mild Steel		Some
78	Ti	.190	910	277	Mild Steel		Some
79	Ti	.155	600	183	Mild Steel		Some
80	Ti	.148	518	158	Mild Steel		No
81	Ti	.89	520	159	Mild Steel		Some
82	Ti	.89	401	122	Mild Steel		No

* large sheet

** cube-and-round

Run No.	Projectile Mat'l	Projectile Mass, Gm	Velocity ft/sec	Velocity m/s	Target	Sparks	Kinetic Energy N-M
83	75M2	.46	919	280	Mild Steel	Yes	18
84	75M2	.51	760	231	Mild Steel	Yes	13.6
85	75M2	.53	609	186	Mild Steel	Some	9.2
86	75M2	.55	523	159	Mild Steel	Some	6.9
87	75M2	.55	619	189	Mild Steel	Some	9.8
88	75M2	.51	449	137	Mild Steel	Some	4.8
89	75M2	.32	475	145	Mild Steel	Some	3.4
90	75M2	.26	367	112	Mild Steel	Some	1.6
91	75M2	.21	47	14	Mild Steel	No	.21
92	75M2	.25	42	13	Mild Steel	No	.22
93	Zr	.64	1514	461	Dural	Some	68
94	Zr	.64	867	264	Dural	No	22
95	Zr	.64	1303	397	Dural	Some	50
96	Ti	.31	863	263	Mild Steel	No	10.4
97	Ti	.30	965	294	Mild Steel	Some	13
98	Ti	.30	899	274	Mild Steel	Some	11.3
99	Ti	.30	958	292	Mild Steel	Some	12.7
100	Ti	.85	896	273	Mild Steel	Some	32
101	Ti	.86	827	252	Mild Steel	Some	27
102	Ti	.86	794	242	Mild Steel	Some	25
103	75M2	1.42	801	244	Mild Steel	Yes	42
104	75M2	1.45	850	259	Mild Steel	Yes	49
105	75M2	1.43	787	240	Mild Steel	Yes	41

Run No.	Projectile Mat'l	Projectile Mass, Gm	Velocity ft/sec	Velocity m/s	Target	Sparks	Kinetic Energy N-M
106	Ti	.30	978	298	Dural 1.9 mm	Some	13 *
107	Ti	.30	988	301	Dural 1.9 mm	No	14 *
108	Zr	.93	784	239	Dural 6.4 mm	Yes	26 **
109	Ti	.30	826	252	Mild Steel	Some	9.5
110	Ti	.30	741	226	Mild Steel	Some	7.7
111	Cu	1.88	2422	738	Copper	-	512
112	Cu	1.88	2425	739	Copper	Yes	512
113	Cu	1.88	2135	651	Copper	Yes	398
114	Cu	1.91	1563	476	Copper	Some	215 ***
115	Cu	1.88	3843	1171	Copper	Yes	1289
116	Cu	1.88	3569	1087	Copper	Some	1111 ****
117	Cu	1.88	3404	1038	Copper	Some	1013
118	Cu	1.89	3266	995	Copper	Some	930 *****
119	Cu	1.93	2811	856	Copper	No	711
120	Al	.19	1763	537	Steel Armor	Some	27
121	Al	.19	2023	617	Steel Armor	Yes	36
122	Al	.19	2978	908	Steel Armor	Yes	78
123	Al	.19	1539	469	Steel Armor	No	21

* loose mount

** solid mount

*** nothing on Polaroid

**** very large hole diameter

***** only glow

Run No.	Projectile Mat'l	Projectile Mass, Gm	Velocity ft/sec	Velocity m/s	Target	Sparks	Kinetic Energy N-M
124	Al	.19	1411	430	Steel Armor	No	18
125	Al	.19	1161	354	Steel Armor	No	12
126	Al	1.04	1568	478	Steel Armor	Yes	120
127	Al	1.04	1156	352	Steel Armor	Yes	64
128	Hf	.90	758	231	Mild Steel	Yes	24
129	Hf	.90	-	-	Mild Steel	Yes	-
130	Hf	.90	764	233	Mild Steel	Yes	24
131	Hf	.90	748	228	Mild Steel	Yes	23
132	Hf	.90	696	212	Mild Steel	Yes	20
133	Hf	.91	653	198	Mild Steel	Some	18
134	Ti	.30	941	287	Mild Steel	Some	12.3
135	Ti	.30	902	275	Dural 6.4 mm	Some	11.3
136	Zr	.88	730	222	Mild Steel	Yes	22
137	Zr	.89	774	236	Mild Steel	Yes	25
138	Zr	.88	761	232	Mild Steel	Yes	24
139	Ti	.30	963	293	Dural 6.4 mm	No	12.9
140	Ti	.85	551	168	Dural 6.4 mm	No	12
141	Ti	.85	772	203	Mild Steel	Yes	17.5
142	Ti	.85	500	152	Mild Steel	Some	9.8
143	Cu	2.16	2838	865	Steel Armor	Yes	808
144	Cu	2.15	1102	336	Steel Armor	Some	121
145	Cu	2.15	780	238	Steel Armor	No	61
146	Cu	2.15	521	159	Steel Armor	No	27
147	Cu	2.14	877	267	Steel Armor	No	7

Run No.	Projectile Mat'l	Projectile Mass, Gm	Velocity ft/sec	Velocity m/s	Target	Sparks	Kinetic Energy N-M
148	Hf	.900	542	165	Mild Steel	Yes	12.2
149	Hf	.905	364	111	Mild Steel	Some	5.6
150	Zr	1.69	3242	988	Dural 1.6 mm	Yes	825
151	Ti	1.73	1704	519	Dural 1.6 mm	Some	233
152	Ti	1.72	2101	640	Dural 1.6 mm	Some	352
153	Ti	1.73	1160	354	Dural 1.6 mm	No	108
154	Ti	1.73	2712	826	Dural 1.6 mm	Yes	587
155	Ti	1.72	2883	879	Dural 1.6 mm	Yes	664
156	MM	0.285	490	149	Dural 6.4 mm	Yes	3.2
157	MM	0.155	424	129	Dural 6.4 mm	Some	1.3
158	MM	0.246	427	130	Dural 6.4 mm	Yes	2.0
159	MM	0.237	396	120	Dural 6.4 mm	Some	1.7
160	MM	0.234	226	69	Dural 6.4 mm	No	0.6

APPENDIX B

Table B-I. Kinetic Energy Comparison of Sparking Thresholds

Projectile	Impact Interface Area, Cm^2	Thresholds Against Dural N-M	Thresholds Against Mild Steel N-M	Thresholds Against Steel Armor N-M
75M2 Misch Metal	0.071	1.7	1.6	-
Hafnium	0.071	-	5.6	-
Titanium	0.071	11.3	9.8	5.1
Zirconium	0.071	27	22	18
Dural	0.071	-	-	64
1095 Steel	0.071	-	-	135
1095 Steel	0.312	345	-	-
Copper	0.453	789	-	121

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